Soft QCD theory

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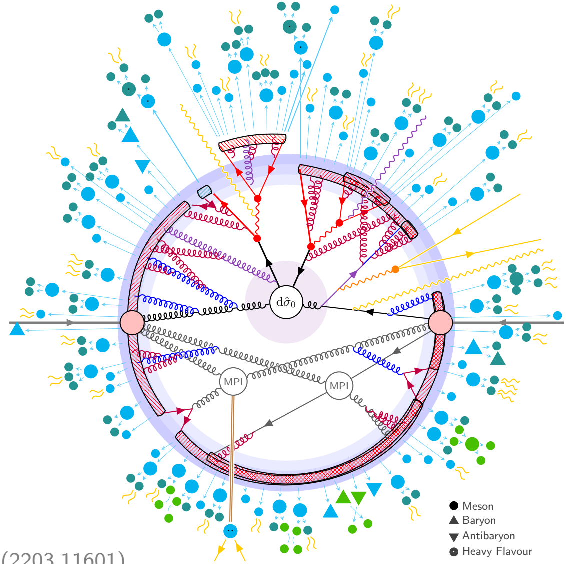
The structure of an LHC pp collision



(2203.11601)

- Hard Interaction
- Resonance Decays
- MECs, Matching & Merging
- FSR
- ISR*
- QED
- Weak Showers
- Hard Onium

- Multiparton Interactions

- Beam Remnants*
- Strings
- Ministrings / Clusters
- Colour Reconnections
- String Interactions
- Bose-Einstein & Fermi-Dirac
- Primary Hadrons
- Secondary Hadrons
- Hadronic Reinteractions

(: incoming lines are crossed)*

Event generators

Complexity addressed by "divide and conquer" in event generators.

(1101.2599, 2203.11110) Generators used to

- predict event properties, for detector and trigger design,
- correct data for acceptance and smearing, and
- interpret data in terms of underlying physics mechanisms.

Current general-purpose event generators for hard + soft physics:

- HERWIG (1912.06509)
- PYTHIA (2203.11601) (new 300+ pages guide!)
- SHERPA (1905.09127)

Special generators for hard matrix elements (as input to above):

- MADGRAPH5_AMC@NLO (1405.0301)
- POWHEG BOX (1002.2581)

Many generators for (soft) QCD, heavy ions and cosmic rays

- EPOS (1306.0121)
- ...

Multiparton interactions (MPIs) – 1

MPIs essential to explain bulk properties of events, e.g. inclusive multiplicity distributions. Theory and modelling still debated.

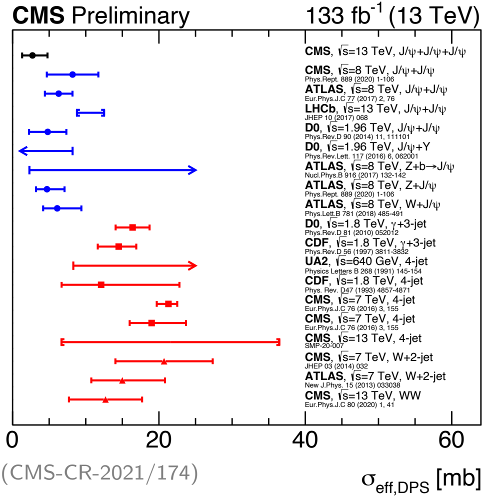
(Adv.Ser.Direct.High Energy Phys. 29 (2018) 1)

Double Parton Scattering (DPS):

$$\sigma_{A,B}^{\mathrm{DPS}} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{\mathrm{eff,DPS}}}$$

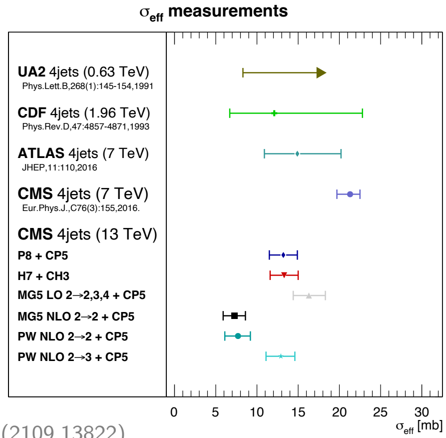
where $m = 1$ if $A = B$ and $m = 2$ if $A \neq B$.

Important confirmation but tests only a tiny fraction of high-$p_\perp$ events.



(CMS-CR-2021/174)

Background modelling nontrivial, especially when jets are involved. Higher orders relevant for this.



(2109.13822)

Full model range even larger spread!

For Gaussian matter distribution expect

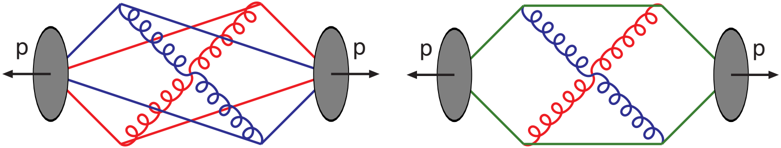
$$\sigma_{\mathrm{eff}} \approx 20 \text{ fm} .$$

Lower $\sigma_{\mathrm{eff}} \Rightarrow$ "hot spots"?

Enhanced DPS rate should dampen at small $p_{\perp}$ scales. Not seen in 3 J/ψ.
(CMS-CR-2021/174)
Probe with $c\bar{c}c\bar{c}$ events?

Colour reconnection (CR)

MPIs + parton showers ⇒ many partons in an event
⇒ colour fields ("strings") run criss-cross.
CR: fields rearrange, to (mainly) reduce string length:



Two main confirmations:

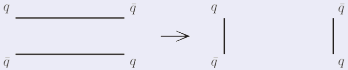
- $\langle p_\perp \rangle(n_{\mathrm{ch}})$ is steadily rising in $\mathrm{pp}/\overline{\mathrm{p}}\mathrm{p}$ data (UA1, Tevatron, LHC), but would be (almost) flat if no CR.
- Combined LEP data on $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^- \to \mathrm{q}_1\overline{\mathrm{q}}_2\mathrm{q}_3\overline{\mathrm{q}}_4$ is best described with 49% CR, 2.2σ away from no-CR.

  (hep-ex/0612034)

Colour reconnection models

“Recent” PYTHIA option: QCD-inspired CR (QCDCR) (1505.01681):

Ordinary string reconnection

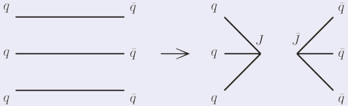


(q$\bar{\text{q}}$: 1/9, gg: 1/8, model: 1/9)

Double junction reconnection

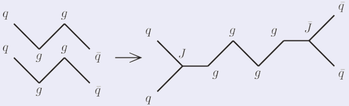
(qq: 1/3, gg: 10/64, model: 2/9)

Triple junction reconnection

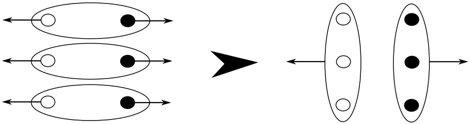


(q$\bar{\text{q}}$: 1/27, gg: 5/256, model: 2/81)

Zipping reconnection

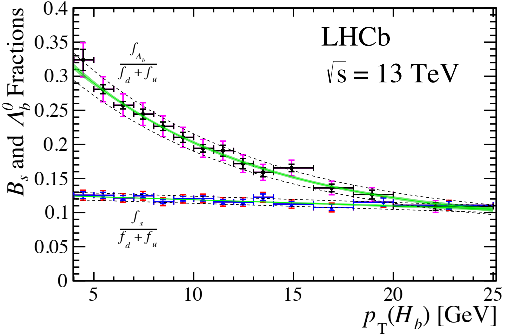


(Depends on number of gluons)



Triple-junction also in HERWIG cluster model. (1710.10906)

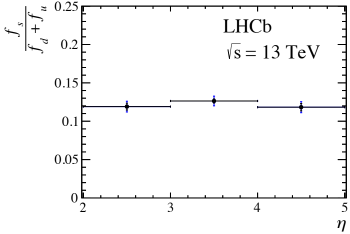
The beauty baryon enhancement

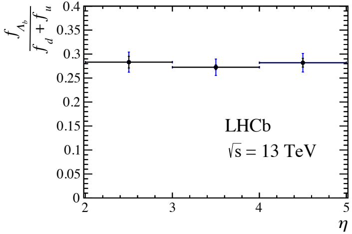


In 2019 LHCb found enhancement of Λ_b^0 production at small $p_\perp$, but flat in η.

(1902.06794)

No model comparisons.

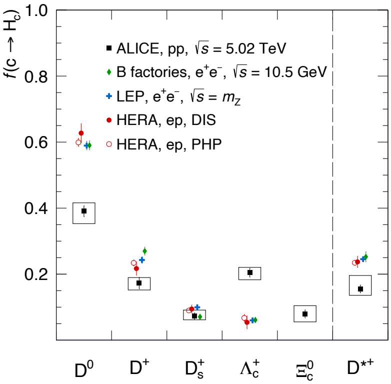


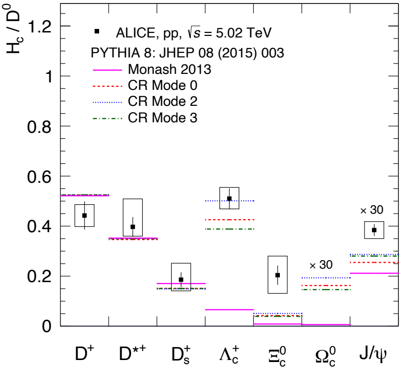


The charm baryon enhancement

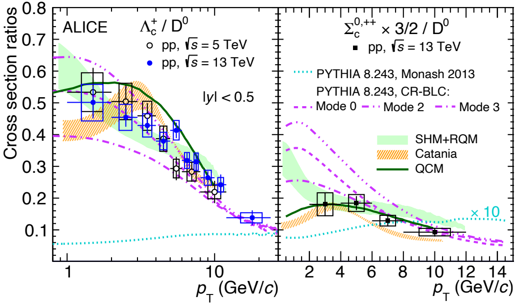
In 2017/21 ALICE found/confirmed strong enhancement of charm baryon production, relative to LEP, HERA and default PYTHIA.

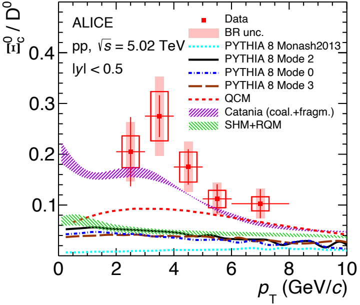
(1712.09581, 2105.06335)

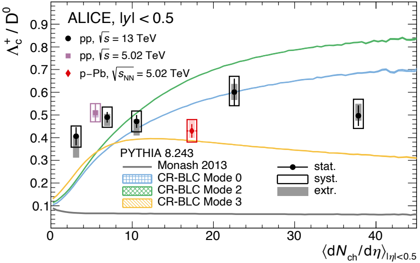




The QCDCR model does much better, with junctions ⇒ baryons.







(2106.08278, 2105.05616, 2111.11948)

QCDCR does well
for some distributions,
less so for others.
Improvements needed,
but good starting point.

Models of and conclusions on particle composition

Other models, in a heavy-ion physics spirit:

- QCM: Quark (re)Combination Mechanism, with co-moving light quarks being picked up. (1801.09402)
- SHM+RQM: Statistical Hadronization Model + Relativistic Quark Model. Thermo-statistical production with extensive feeddown from heavier charm baryon states. (1902.08889)
- Catania: use AA models of quark–gluon plasma formation. Coalescence of nearby quarks at small $p_{\perp}$, while "normal" fragmentation at higher $p_{\perp}$. (2012.12001)

Tentative conclusion:

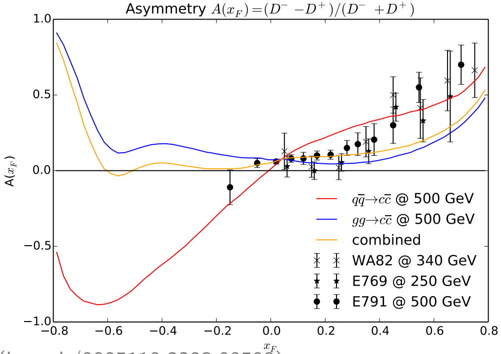
- "Vacuum" evolution at large $p_{\perp}$, like in $\mathrm{e}^{+}\mathrm{e}^{-}$ and ep.
- Collective effects take over at small $p_{\perp}$, where MPIs give close-packing of quarks/gluons/strings/clusters/hadrons.

Breakdown of jet universality, like for strangeness!

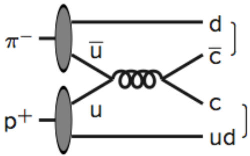
Beam drag effects

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g. in $\pi^- \mathrm{p}$:

$$A(x_\mathrm{F}) = \frac{\sigma(\mathrm{D}^-) - \sigma(\mathrm{D}^+)}{\sigma(\mathrm{D}^-) + \sigma(\mathrm{D}^+)}$$



(hep-ph/0005110,2203.09503)

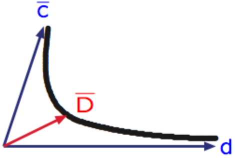


If low-mass string e.g.:

$\bar{\mathrm{c}}\mathrm{d} : \mathrm{D}^-, \mathrm{D}^{*-}$

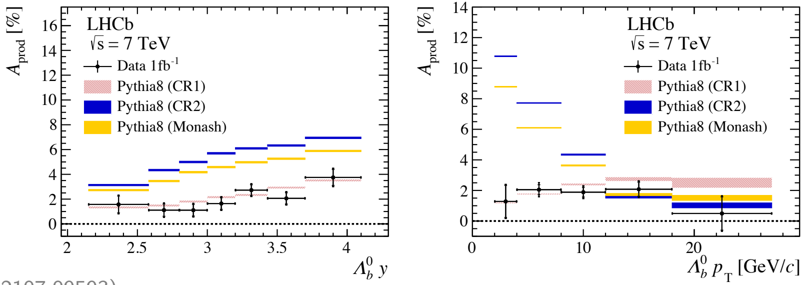
$\mathrm{cud} : \Lambda_\mathrm{c}^+, \Sigma_\mathrm{c}^+, \Sigma_\mathrm{c}^{*+}$

$\Rightarrow$ flavour asymmetries



Can give D “drag” to larger x_F than c quark.

Bottom asymmetries

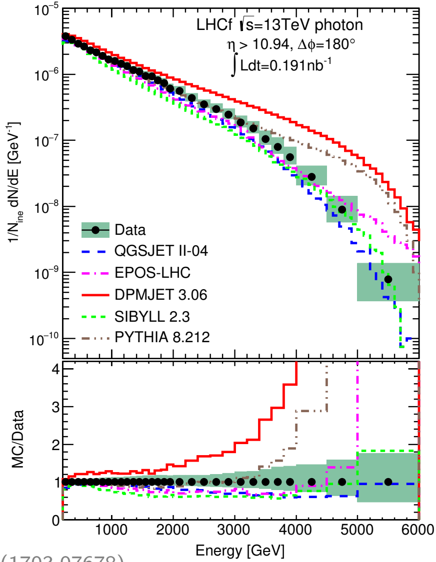


(2107.09593)

$$A(y), A(p_\perp) = \frac{\sigma(\Lambda_b^0) - \sigma(\overline{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\overline{\Lambda}_b^0)}$$

CR1 = QCDCR, with no enhancement at low $p_\perp$.
Enhanced Λ_b production at low $p_\perp$, like for Λ_c, dilutes asymmetry?
Asymmetries observed also for other charm and bottom hadrons.

Warning: fragmentation function formalisms unreliable at low $p_\perp$.
May lead to incorrect conclusions about intrinsic charm.



(1703.07678)

Forward region important for cosmic-ray physics ⇒ LHCf.

Also for FASER/. . . and the Forward Physics Facility.

Wide spread of predictions; no generator perfect.

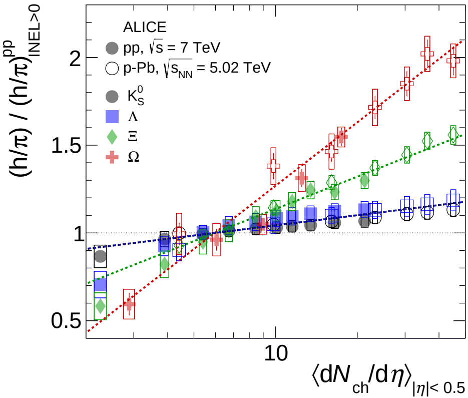
Requires improved modelling of

- beam remnant,
- diffraction, and
- $c/b/\tau$ production.

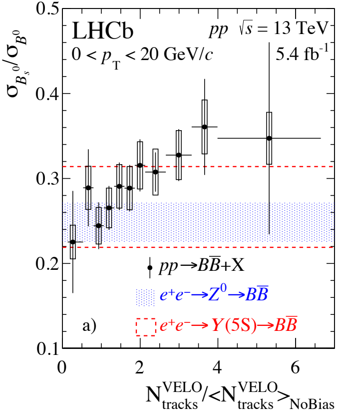
Studies/tunes under way.

(2203.05090)

Strangeness enhancement



(1606.07424)



(2204.13042)

Strangeness enhancement at high multiplicity — previous major discovery — now also observed in $\mathrm{B_s^0/B^0}$ by LHCb.

Approximately described by colour ropes or core–corona models.

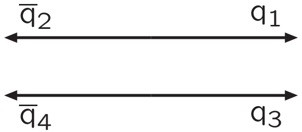
Rope hadronization

Dense environment $\Rightarrow$ several intertwined strings $\Rightarrow$ **rope**.

Sextet example:

$3 \otimes 3 = 6 \oplus \overline{3}$

$C_2^{(6)} = \frac{5}{2} C_2^{(3)}$



At first string break $\kappa_{\mathrm{eff}} \propto C_2^{(6)} - C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \frac{3}{2}\kappa$.

At second string break $\kappa_{\mathrm{eff}} \propto C_2^{(3)} \Rightarrow \kappa_{\mathrm{eff}} = \kappa$.

Multiple $\sim$parallel strings $\Rightarrow$ random walk in colour space.

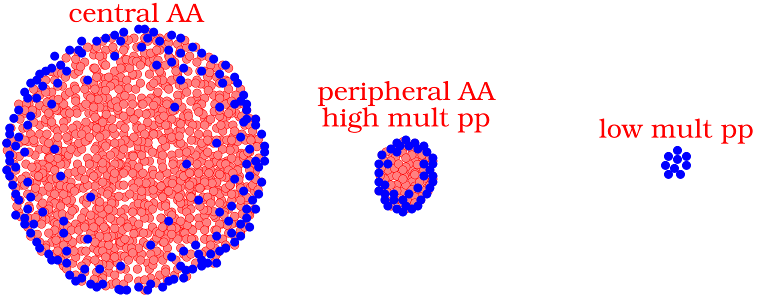
Larger $\kappa_{\mathrm{eff}} \Rightarrow$ larger $\exp\left(-\frac{\pi m_{\mathrm{q}}^2}{\kappa_{\mathrm{eff}}}\right) \Rightarrow$ more strangeness and baryons

mainly agrees with ALICE (but p/π overestimated).

(1412.6259, 2202.12783)

The core–corona solution

Smooth transition from low-multiplicity pp all the way to AA implemented in EPOS by mixture of discrete strings and continuous quark–gluon plasma (QGP).

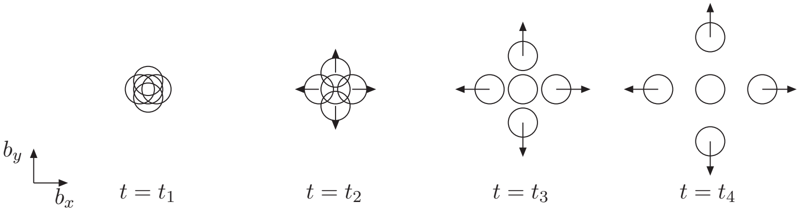


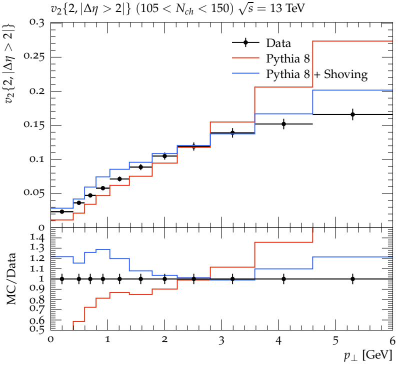
core => hydro => statistical decay ($\mu = 0$)
corona => string decay

(K. Werner, Lund 2017)

Still open question whether high-multiplicity pp can be fully described without invoking QGP.

Shove / repulsion





Overlapping string at early times can give repulsive push, so strings get transverse motion, imparted to hadrons produced from them.

Can give ridge and flow, in azimuth and $p_\perp$.

(1612.05132, 1807.05271, 1912.09639, 2010.07595).

Also ALICE. (2107.11209)

Some further interesting experimental studies

- Observation of an odderon. D0 + TOTEM (2012.03981).
- Ratio $f_{\mathrm{s}}/f_{\mathrm{d}} \approx n(\mathrm{B}_s^0)/n(B^0)$ slightly decreasing with $p_\perp$, consistent with higher density at small $p_\perp$. LHCb (2103.06810).
- Direct observation of a "dead cone" effect around D mesons, in agreement with models. ALICE (2106.05713).
- The b quark fragmentation function $f(z)$, $z \approx p_{\perp\mathrm{B}}/p_{\perp\mathrm{b}}$ and the B transverse distribution in a jet mostly in good agreement with generators. ATLAS (2108.11650).
- Also b jets in top decays show good agreement with generators. ATLAS (2202.13901).
- New PYTHIA tunes, including for the QCDCR model, show comparable agreement with the default one for generic event properties, and sharpen constraints on the top mass uncertainty from CR. CMS (2205.2905).
- Bose–Einstein effects continue to be explored, while modelling lags behind. CMS (1910.08815) and ATLAS (2202.02218).

Some further interesting theoretical ideas – 1

- Further develop and tune cluster hadronization, and a model for colour reconnection. In the latter, the distance between two partons (i, j) is $d_{ij} = \Delta P_{ij} \cdot \Delta R_{ij} / C$, where the first factor involves momentum separation, the second transverse spatial one, and C is related to colour factors. SHERPA (2203.11385).
- Trace space–time evolution of parton shower to define production points of cluster endpoints. Cluster (i, j) "size" is $R_{ij}^2 = \Delta r_{ij}^2 / d_0^2 + \Delta y_{ij}^2$. Allow rearrangements that reduce cluster sizes in total. HERWIG (1909.08850).
- View colour reconnection as a consequence of evolution in colour space beyond the leading-colour ($N_C \to \infty$) limit. HERWIG (1808.06770, 2204.06956).
- Use cluster fragmentation ideas to describe the hadronization of a quark–gluon plasma. HERWIG (2012.08493).

Some further interesting theoretical ideas – 2

- Close-packing of strings ⇒ (continuously) larger string tension ⇒ "thermodynamical" fragmentation. PYTHIA (1610.09818).
- String tension decreasing with time, affected particle production proportions. PYTHIA (2005.06219).
- Modelling the space–time structure of string fragmentation (1808.04619) opens up for an implementation of hadronic rescattering (1911.12824, 2005.05658, 2103.09665), including formation of molecular states (2108.03479). PYTHIA.
- Improved ansatz for flavour production in string fragmentation. PYTHIA (2201.06316).
- Deep learning opens new approaches to event generation (2203.07460), e.g. hadronization (2203.04983, 2203.12660).
- Will need to adapt to new computing styles, e.g. graphics processors.

Summary and outlook

- Many poorly understood soft-physics aspects, notably
  - multiparton interactions,
  - colour reconnection, and
  - hadronization.
- LHC data has revolutionized the picture of soft physics:

  Goodbye jet universality!
- This has led to a renewed phenomenology interest:

  Welcome new mechanisms!
- Still some way to go before a new unified picture is in place, covering the evolution from $\mathrm{e}^+\mathrm{e}^-$ to low-n_{ch} pp to AA.
- Should prepare for future colliders: EIC, ILC, FCC, . . . , and
- strengthen ties to fixed-target (ν) and cosmic-ray studies.

Some interesting other presentations at LHCP

- Francesco Prino (Mon): Modification of hadronization in heavy ion collisions
- Mateusz Dyndal (Mon): Ultra-peripheral collisions
- Jaime Norman (Mon): Heavy-flavour production at the LHC
- Matt Durham (Wed): Heavy flavor production and hadronization in small systems
- Norbert Novitzky (Wed): Small-x QCD and hadronization
- Christoph Royon (Wed): The discovery of the odderon by the D0 and TOTEM collaborations
- Blair Daniel Seidlitz (Thu): Soft hadron production and collectivity in small systems
- Georgy Kornakov (Thu): Hadron-hadron QCD interactions
- Davide Zuliani (Thu): Precision QCD measurements

Also posters by Suman Deb, Baidyanath Sahoo, Giuseppe Piparo, Theraa Tork, Sonali Padhan, Nameeqa Firdous, . . .